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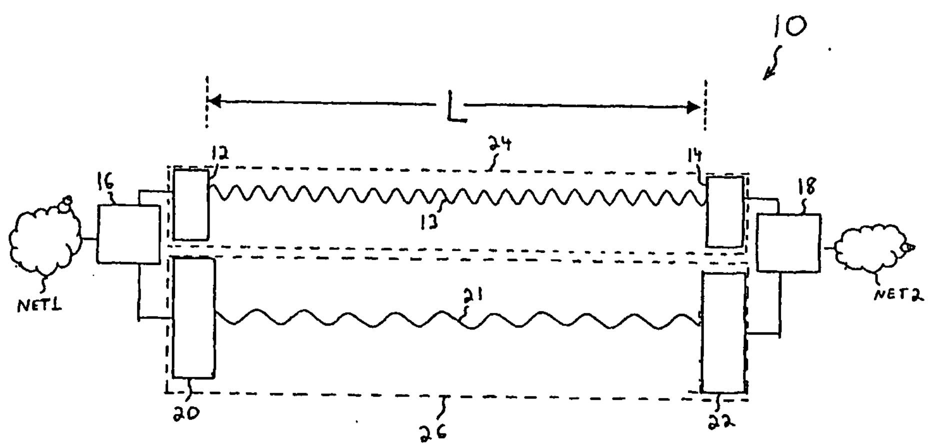

(57) Abstract: A hybrid link (Fig. 1) and method for extending the all-weather range of a broadband wireless communication system using a hybrid combination of free-space optical communication channels (12) and non-optical channels (20). Examples of non-optical channels are microwave or millimeter-wave communication channels. Each communication channel in the system is engineered to achieve an optimum channel margin. Channel margins are based on a predetermined percent for channel availability under weather conditions ranging from dense fog or excessive rain to light drizzle. In clear weather, the link is designed to communicate at a data rate equal to the sum of the individual data rates of both channels. Use of the hybrid link increases the range such that the transmitters and receivers of the system may be placed physically farther apart. The hybrid link provides protection for transmitted data using the electromagnetic complementarity of the frequencies used for data transmission in various weather conditions.

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HYBRID WIRELESS COMMUNICATION SYSTEM UTILIZING A COMBINATION OF OPTICAL AND-NON-OPTICAL CHANNELS

Field of the Invention

This invention relates to wireless communication systems, and more particularly to a broadband wireless communication system designed to work in varying atmospheric conditions.

Background of the Invention

The rapid growth of the communications industry has created a tremendous demand for reliable high-speed data communication systems. In particular, there is a growing demand for data communication systems that can provide the bandwidth required to deliver high quality data at high speeds. One example of an area where communications demands have been rapidly increasing is the worldwide information system commonly known as the Internet. Businesses and consumers are among the growing number of Internet users. Businesses have a need for increasingly sophisticated electronic commerce technologies for use in the processing of a growing number of online Internet-based transactions. Such technologies and the transactions they facilitate currently require, and will continue to require for the foreseeable future, more communications bandwidth for the delivery of valuable commercial content and related transactional information.

Consumers will also increasingly demand more from such communications services. Among their growing list of demands will be a demand for more compelling, data-rich content that is embedded within data of varying types, from text and audio data to high-speed real-time video streaming. A number of telecommunications companies currently provide their communications services over the existing telecommunications infrastructure to the local or regional trunk. The distance between this trunk and the telephone connection in homes and businesses has come to be known as the "last mile." The delivery to consumers of the high-bandwidth data which they will ultimately demand over this last mile of telecommunication links has been proven to be extremely costly. A variety of solutions have been proposed to enable Internet service and data content providers to deliver massive amounts of data over this "last mile," but no one commercial solution has yet to solve this pressing data communications problem.

A number of telecommunications technologies have been developed to deliver data at different data rates, over different distances, and in different types of weather conditions. Twisted pair coaxial cable has been the traditional workhorse of the telecommunications industry, but it has been superseded in many respects by fiber optics which provides significantly greater bandwidth. Both of these technologies have been used by long distance telecommunications providers for years. In the case of wireless technologies, radio-frequency communication systems, microwave communication systems, millimeter-wave communication systems, and free-space optical communication systems have also been used in different capacities by companies in this industry. The higher frequency microwave and millimeter wave systems are particularly desirable because information carrying capacity is directly proportional to frequency.

Modern broadband wireless communications occur over a wide range of licensed and unlicensed frequencies ranging from the television-bands at 54 to 890 MHz up to optical frequencies. Of particular interest are frequencies greater than 1 GHz since the bandwidth in this range is sufficient to achieve high bit-rate communications. Unlicensed bands include the ISM (Industrial, Scientific, and Medical) band at 2.4 GHz, the new UNII bands around 5 GHz, the 60 GHz band at which frequency atmospheric oxygen absorbs very strongly, and optical frequencies. The 2.4 GHz band is becoming increasingly "cluttered" not only by data links but also by microwave ovens, remote telephones, and a new kind of high-efficiency fluorescent light fixture developed initially for outdoor use. This frequency band provides no protection to telecommunications users. Electromagnetic interference associated with the recently reserved UNII frequency band (5.1 GHz) are less severe. Although this band is unlicensed and may not be used for industrial, scientific, or medical applications, it has been reserved for use in telecommunications applications.

The propagation of electromagnetic waves through the atmosphere has been the subject of intense research dating at least as far back as World War II. A myriad of meteorological factors can have deleterious effects on the atmospheric propagation of electromagnetic waves, including scintillation, fog, rain, and pollution. The statistical distribution of these factors around the world is extremely complex, especially in and around the world's major population centers. The distribution of particle sizes corresponding to these factors is equally complex. The electromagnetic wavelengths

relevant to wireless communications span five or more orders of magnitude (specifically, from the sub-micron optical wavelengths to centimeter-scale 28 GHz wavelengths to decimeter-scale wavelengths at the unlicensed 2.4 GHz ISM band). Although Maxwell's equations deterministically predict the interaction of electromagnetic waves with atmospheric media, the mathematical analysis of this interaction significantly increases in complexity whenever the length of an electromagnetic wave is comparable to the size of an atmospheric scatterer, such as a particle of fog, since strong wave-particle interactions occur under these conditions. A proper and thorough analysis of complex wave-particle interactions necessarily requires the use of higher-order mathematics to describe these interactions, thus sharply limiting the field of expertise to individuals skilled in both mathematics and physics. The complexity of this problem increases even more due to the lack of a "typical" statistical distribution of particle sizes in fog. Based on experimental data, the distribution of such particles will vary as a function of several factors including, but not limited to, location, temperature, relative humidity, and the presence of dust in the air through which the electromagnetic waves propagate.

The following additional factors also greatly influence the analysis of the effect of weather on the propagation of electromagnetic waves: (1) the rich complexity of weather patterns, including high-resolution variations in the temporal and geographical distribution of fog and rain, (2) the need to incorporate statistical particle size distributions for fog and rain into the scientific and mathematical analysis of the propagation of electromagnetic waves through inhomogeneous media; and (3) the dearth of high-resolution fog and rain data at geographical locations other than airports.

With regard to a particular set of atmospheric conditions, free-space optical communication systems provide a number of advantages over other wireless communication technologies. Among the advantages of such systems are high data rates, increased security, no licensing or spectrum allocation requirements, portability, rapid deployability, and, when compared specifically to fiber optic cabling, significantly lower economic deployment costs. However, these systems also have certain major disadvantages. The two principle disadvantages of a free-space optical communication system are its susceptibility to atmospheric turbulence, also known as scintillation, and atmospheric attenuation. These effects can render the optical systems virtually inoperable over extended ranges under certain atmospheric conditions.

The use of lasers for clear-weather free-space optical communications has evolved steadily over the past forty years. Both intermittent, extended-range communication over long distances (extending to inter-planetary distances under intermittently clear-weather conditions), and more reliable communications over much shorter distances (as determined, for example, by Mie scattering effects of fog on optical visibility) have been performed. While free-space optical communication links require acceptable levels of atmospheric visibility, their data rates can be extremely high; up to 10 Gbps per wavelength has been demonstrated using wavelength-division multiplexing ("WDM") on four 2.5 Gbps WDM wavelengths. The process may be scaleable to Tbps (Terabits per second) communications via the use of higher data rates on each wavelength and via the use of DWDM (dense wavelength division multiplexing).

Fog can have a catastrophic impact on the performance of optical communications links. Prior art references teach that the attenuating effects of fog on light are both physically and mathematically severe. These references also teach that fog can cause the power in signals transmitted at optical frequencies to drop much more quickly than the rate at which microwave signals are attenuated in rain.

Scintillation is an additional problem in optical communication systems. Scintillation is caused by the deflection of light by atmospheric turbulence. Scintillation produces an effect that is responsible for the "twinkle" in stars and can cause undesirable temporal and spatial fluctuations in transmitted laser beams. Scintillation manifests itself in optical communications as a random fluctuation in light intensity incident on a receiver as a laser beam is periodically deflected off-axis beyond the receive aperture of a detector. Heat convection, in particular, exacerbates the effects of scintillation on a laser beam. However, all of these effects can be partially ameliorated by using multiple transmit/receive apertures, geometrically arranged so that the beam in one aperture twinkles "off," while the beam in a different aperture twinkles "on." By using this approach, on the average, a steady-state signal will be received that has statistical noise properties that are independent of atmospheric conditions.

In some cases, radio-frequency communication systems have been used in a back-up type capacity to provide a low bit-rate alternative to high bit-rate free-space optical communication systems in the event the optical communication system becomes inoperable. The use of such back-up radio-frequency communication systems has been

limited to the transmission of data at data rates considerably less than that provided by a purely optical communication system. Thus, in such systems, if the optical communication portion becomes inoperable, the system can only operate at a severely reduced data transmission rate.

Other combined systems have attempted to use radio frequency systems in series with optical systems. For example, attempts have been made to use a radio-frequency communication system for the transmission of data from a base station to a variety of portable devices, and then use an optical communication system for the transmission of data from the portable devices to the base station. However, such systems suffer from the same atmospheric concerns as those noted above for optical systems and can become inoperable in adverse weather conditions.

Thus, what is needed is a communications system that overcomes the inherent costs, complexities and performance limitations of the various combinations of communication systems and related physical phenomena described above.

Summary of the Invention

The present invention is an improved broadband wireless communication system utilizing a hybrid combination of a free-space optical communication channel with another channel that is transmitted at a non-optical frequency such as a microwave or millimeter-wave frequency. The free-space optical communication channel is deployed in parallel with the non-optical communication channel. Each communication channel in the system can be separately engineered with regard to certain weather conditions so as to implement an optimum channel margin to maximize data throughput. As will be discussed in more detail below, certain factors may influence the specific configuration of the system, including the temporal and spatial distribution patterns of weather conditions such as dense fog and excessive rain, the data switching protocols that are used, and the desired percent availability for each channel and the link as a whole.

The channel margins that are used are based on a predetermined percent of channel availability under wide-ranging weather conditions. The weather conditions for which the channel margins are designed may range from dense fog or excessive rain to light drizzle. Free-space optical channels are more severely attenuated in dense fog while microwave and millimeter-wave channels are more severely attenuated in rain. In clear weather, the link is designed to communicate at a data rate equal to the sum of

the individual data rates on the free-space optical communication channel and the non-optical communication channel. Overall link performance is determined by a bit error rate which is below the predetermined percent availability for the hybrid link.

With regard to the microwave channel, even though microwaves are exponentially attenuated in rain, the scattering effects of fog on optics are both physically and mathematically much worse than the attenuating effects of rain on microwaves. In other words, fog causes the power in signals transmitted at optical frequencies to drop much more quickly than the drop in power of microwave frequency signals in rain. In addition, while both microwave and optical beams are subject to scintillation, the effect at microwave frequencies is negligible (primarily because microwave apertures are large relative to the amount of scintillation-induced deflection experienced by a microwave signal).

The net result of combining a free-space optical communication channel with a non-optical channel is a lengthening of the total distance over which data on either channel can be transmitted. Thus, the transmitter units and receiver units of the system may be placed physically further apart. This is particularly beneficial when such components must be placed on rooftops or in similar locations. The optical/non-optical combination physically protects the data that it transmits via electromagnetic complementarity of the carrier frequencies used for the transmission of data in varied weather conditions. An additional benefit provided by the combination is that it permits data to be transmitted at higher overall data rates regardless of existing weather conditions in both point-to-point and point-to-multipoint architectures and in a variety of protocol-independent computer network topologies, such as rings, meshes, trees, stars, and hubs-and-spokes.

In accordance with another aspect of the invention, there is provided in the hybrid link at least two free-space optical transmit/receive units, at least two other transmit/receive units for the non-optical communications, and at least two switching devices. The switching devices are used for transmitting and receiving data over a meteorological atmospheric range having diverse weather conditions. The two sets of transmit/receive units are deployed in a parallel configuration.

In accordance with another aspect of the invention, the free-space optical transmit/receive units operate on a carrier frequency in a range equal to or greater than 100 THz. In a preferred embodiment, the free-space optical transmit/receive units

operate on a carrier frequency of approximately 180 THz. State-of-the-art free-space optical transmit/receive units can, in principle, transmit and receive up to multiple Terabits per second (Tbps) when operating in this frequency range, particularly via the use of wavelength division multiplexing (WDM). There is no minimum data transmission rate for free-space optical communications. If the non-optical channel is microwave, the microwave transmit/receive unit operates on a carrier frequency in the range between 1 GHz and 30 GHz. State-of-the-art microwave transmit/receive units can transmit up to about 155 million bits per second (155 Mbps) when operating in this frequency range (622 Mbps and 1 Gbps links are also possible depending on the spectral bandwidth available, the coding techniques employed, the range, and other factors). If the non-optical channel is millimeter-wave, the millimeter-wave transmit/receive unit operates on a carrier frequency in a range between 30 GHz and 300 GHz. The millimeter-wave transmit/receive unit can transmit up to one billion bits per second (1 Gbps) when operating in this frequency range. Higher data rates are also possible depending again on the available spectral bandwidth, coding, etc. Various levels of the Optical Carrier standards may be supported at these transmission rates, including OC-3, OC-12, OC-18, OC-48 and OC-192. Standard Ethernet levels, such as 10 Gbps, may also be supported.

In accordance with still another aspect of the invention, the switching devices that are coupled to the transmit/receive units are capable of generating and combining multiple data streams. Thus, the switching device on the transmitting end generates two data streams from a single data stream received from a network for transmission. At the receiving end, the receiving device combines the two received data streams into one data stream.

In accordance with yet another aspect of the invention, the data that is transmitted on the free-space optical channel may be different than the data that is transmitted on the non-optical channel of the hybrid link. For example, the data transmitted on the two channels can be from different portions of a single data stream received from a network, or they can be from entirely different data streams received from a network. In other words, the optical channel may transmit a subset of the data from the network that is different from the subset of data that is transmitted by the non-optical channel.

In accordance with another aspect of the invention, the data rate of the non-optical channel in clear weather conditions is a substantial percent of the data rate of the free-space optical channel. In one embodiment, this predetermined percentage is 10 percent. In accordance with another aspect of the invention, the length of the hybrid optical/non-optical link is at least a predetermined number of times further than the length of a single free-space optical channel that is designed to operate in dense fog. In one embodiment, the predetermined number is three times further. In accordance with another aspect of the invention, the length of a hybrid link having a free-space optical channel in parallel with a non-optical channel is at least a predetermined number of times further than the length of a microwave channel that is designed to operate in rain. In one embodiment, the predetermined number is two times further. In accordance with another aspect of the invention, the data rate of the hybrid link in clear weather conditions is the sum of the data rate on the free-space optical channel and the data rate on the non-optical channel.

In accordance with another aspect of the invention, the hybrid link includes a switching device for receiving multiple data streams, the switching device containing at least two input buffers, circuitry for processing and combining the data streams, and one or more transmission means for transmitting data streams to one or more networks.

In accordance with another aspect of the invention, the hybrid link includes a switching device for transmitting multiple data streams, wherein the switching device contains at least one input buffer, circuitry for processing and dividing a single data stream into multiple data streams, at least two output buffers, an optical transmitter circuit coupled to a free-space optical channel transmit/receive unit, and a non-optical channel transmitter circuit coupled to a non-optical channel transmit/receive unit. The input buffer receives and stores a data stream from a network. The processing circuitry produces at least two output data streams from the input data stream provided by the input buffer. One of the output buffers is coupled to an optical transmitter circuit and a second output buffer is coupled to a non-optical transmitter circuit. The optical transmitter circuit transmits a first output data stream generated by the decoder to the optical transmit/receive unit. The non-optical transmitter circuit transmits a second output data stream generated by the decoder to the non-optical transmit/receive unit. The second data stream may be comprised of different data than the first data stream. Also, the input data stream may be comprised of first and second portions, or first and

second input data streams, and the first and second output data streams may comprise the first and second portions, or the first and second input data streams.

In accordance with another aspect of the invention, a method for characterizing the properties of the atmospheric regions in which the hybrid link may be used for transmitting data is provided. More particularly, a method is provided for determining the statistical availability of a hybrid link based on knowledge of the weather conditions in the region where the hybrid link is to be deployed. The method determines a priori the degree to which the optical and non-optical frequencies will likely be attenuated in varying locations, such that the particular hybrid link can be designed to operate effectively in the given climate.

Brief Description of the Drawings

The foregoing aspects and many of the attendant advantages of this invention will become more readily appreciated as the same become better understood by reference to the following detailed description, when taken in conjunction with the accompanying drawings, wherein:

FIGURE 1 is a block diagram of a hybrid wireless communication system including an optical wireless communication channel and a non-optical wireless communication channel in accordance with the present invention;

FIGURE 2 is a block diagram showing the transmission of a single data stream having multiple data packets;

FIGURE 3 is a block diagram showing the transmission of a data stream in two portions;

FIGURE 4 is a block diagram showing the transmission of multiple data streams;

FIGURE 5 is a flow chart showing a process for transmitting data using a hybrid link;

FIGURE 6A is a table showing experimentally determined rates of attenuation in fog, excessive rain, heavy rain, and drizzle for certain transmission frequencies; and

FIGURE 6B is a table showing additional experimentally determined rates of attenuation in fog, excessive rain, heavy rain, and drizzle for certain transmission frequencies.

Detailed Description of the Preferred Embodiment

The present invention is directed to a hybrid wireless link for extending the range of a free-space optical communication link. The hybrid link includes a free-space optical communication channel and a non-optical high frequency communication channel in a parallel configuration, a switching device for transmitting data streams, and a switching device for receiving data streams. The non-optical high frequency communication channel may be in a frequency range such as the microwave or millimeter-wave range. In general, one or more data streams are transmitted through an atmospheric range from a pair of transmitting units on one side of the range to a pair of receiving units on the other side of the range.

Hybrid links may be combined in various ways with each other and with conventional links to create local, regional and international data transmission networks. Hybrid links used to create global networks may be specially engineered for and deployed in varying weather conditions around the world based on prior knowledge of prevailing weather conditions in economically important geographic locations. More specifically, the hybrid link presented herein may be used as part of a comprehensive system that allows for the rapid identification and mapping of suitable channel margins for each hybrid link that is to be deployed in a global network based on prevailing worldwide weather conditions.

FIGURE 1 depicts a hybrid link 10 of link length L for data transmission across an atmospheric range. The hybrid link 10 includes two free space optical transmit/receive units 12 and 14, one on each side of the link for transmitting and receiving an optical frequency signal 13. The hybrid link 10 also includes two non-optical high frequency transmit/receive units 20 and 22 on each side of the link for transmitting and receiving a non-optical frequency signal 21, such as a microwave or millimeter-wave signal. In a preferred embodiment, the non-optical transmit/receive units 20 and 22 may include antennas taking the form of traditional concave parabolic dishes, although it will be understood by those in the art that such antennas may take on any number of different forms. It will also be understood by those in the art that the transmit/receive units 12, 14, 20 and 22 may be designed to transmit data streams either unidirectionally or bidirectionally. The hybrid link 10 also includes a first switching device 16 for transmitting data streams received from a first network NET1, and a

second switching device 18 for retransmitting the received data to a second network NET2.

An optical communication channel 24 includes the first free-space optical transmit/receive unit 12 and the second free-space optical transmit/receive unit 14. In one embodiment, the carrier frequency is in a range equal to or greater than 100 THz. In a preferred embodiment, the optical communication channel 24 transmits the data signal 13 at a carrier frequency of 180 THz. A non-optical high frequency communication channel 26 includes the first high frequency transmit/receive unit 20 and the second high frequency transmit/receive unit 22. If the communication channel 26 is carried in the microwave range, the data signal 21 will typically be transmitted at a carrier frequency in a range between 1 GHz and 30 GHz. In a preferred microwave embodiment, the communication channel 26 transmits the data signal 21 at a carrier frequency of 28 GHz. If the communication channel 26 is carried in the millimeter-wave range, the data signal 21 will typically be transmitted at a carrier frequency in a range between 30 GHz and 300 GHz. In a preferred millimeter-wave embodiment, communication channel 26 transmits the data signal 21 at a carrier frequency of either 39 GHz or 60 GHz. It is to be understood that the hybrid link 10 may be used for data transmission between sections of the same network or to entirely different networks regardless of the data communication protocols used on these networks.

It will be understood that the hybrid link 10 may support data transmission rates according to a variety of industry standards. For example, the Optical Carrier standard includes a number of possible levels. As defined in *Newton's Telecom Dictionary, 16th Edition,* various possible OC levels include OC-1, OC-3, OC-9, OC-12, OC-18, OC-24, OC-36, OC-48, OC-192, and OC-256. OC-1 is defined at being 51.840 million bits per second, and is stated to be the optical counterpart of STS-1 (synchronous transport signal-1), which is the fundamental signaling rate of 51.840 Mbps on which the SONET (Synchronous Optical NETwork) hierarchy is based. All higher levels are direct multiples of OC-l (i.e., OC-3 = 3 X OC-1, or 155.52 Mbps). Another standard is in regard to the Ethernet, which utilizes data transmission rates such as 10 Mbps. All higher levels of Ethernet, Gigabit Ethernet, and 10 Gigabit Ethernet service provide data rates which are factors of ten higher than 10 Mbps (e.g. 100 Mbps, 1 Gbps, 10 Gbps, etc.)

As shown in FIGURE 2, a data stream 31, consisting of one or more data packets, is received from the network NET1 by a switching device 16. In this embodiment, identical copies of the data packets A, B, and C of the data stream 31 will be transmitted on both the optical communication channel 24 and the non-optical communication channel 26. The data stream that is transmitted by the optical channel is designated as data stream 31a, while the data stream that is transmitted by the non-optical channel is designated as data stream 31b. In this arrangement, the communication channels 24 and 26 are both used to maximize the likelihood of successful data transmission through the hybrid link 10. Thus, in the event dense fog is present on the atmospheric range severely attenuates the optical communication channel 24, data may still be received through the non-optical communication channel 26. Upon receipt of the data transmitted by the second free-space optical transmit/receive unit 14 and the second non-optical transmit/receive unit 22, the data packets will be recombined into the single data stream 31 by the receiving switching device 18 and transmitted to the network NET2. In a preferred embodiment, channels 24 and 26 could be made to support the same bit rate (e.g., OC-3, OC-12, or GbE) and to make use of the telecommunications industry-standard protection protocols such as SONET or SDH in switches 16. SONET BLSR (bidirectional line-switched ring) will double the capacity of the ring under clear weather conditions, as compared to an embodiment in which SONET UPSR is implemented.

FIGURE 3 depicts a data stream 41 that is divided into a first portion 41a and a second portion 41b for transmission through the hybrid link 10. Upon receipt by the switching device 16, the data stream is divided into the two different portions 41a and 41b. The first portion 41a is transmitted on the optical communication channel 24 and the second portion 41b is transmitted on the non-optical communication channel 26. The portions of the data stream are transmitted over the atmospheric range and received by the free-space optical communication transmit/receive unit 14 and the non-optical communication transmit/receive unit 22. The data portions are received by the second switching device 18 and recombined into the data stream 41.

In this arrangement, the switching device 18 receives the portions 41a and 41b of the data stream and reassembles them into a single data stream 41 for transmission to the network NET2. Data transmission in this arrangement is intended to maximize the throughput of the hybrid link. In the event a portion of a data stream is lost due to

adverse weather conditions which severely attenuate a communication channel, the portion of the data stream may be retransmitted consistent with a retransmission policy implemented by an appropriate networking protocol. In a preferred embodiment, the system uses industry-standard retransmission policies such as Internet Protocol or MPLS (multi-protocol label switching) or MP(lambda)S (multi-protocol lambda switching).

FIGURE 4 shows a data stream with different portions consisting of multiple sub-data streams 51, 52, 53, and 54 which are received from the network NET1 by the switching device 16. After receiving each sub-data stream, the switching device 16 transmits the sub-data streams 51 and 52 on the optical communication channel 24 of the hybrid link 10 and transmits the remaining sub-data streams 53 and 54 on the non-optical communication channel 26. The sub-data streams may be received and retransmitted by the switching device 16 in any order consistent with an appropriate switching protocol. The order of transmission of the sub-data streams by the switching device 16 to the optical communication channel 24 and the non-optical communication channel 26 as shown in FIGURE 4 is merely illustrative and may also occur in any alternative order provided by an appropriate switching protocol.

After switching the sub-data streams to the appropriate channels, the sub-data streams are transmitted across the atmospheric range to the free-space optical communication transmit/receive unit 14 and the non-optical communication transmit/receive unit 22, and transmitted to the second switching device 18. One or more input buffers on the switching device 18 receive the data streams. The data streams in the input buffers are subsequently multiplexed into one or more output buffers and then transmitted to the network NET2. The data streams may be transmitted to the network NET2 in the order in which they were received by the switching device 18 or they may be transmitted to the network NET2 using an appropriate switching protocol.

As discussed above, one or more hybrid links 10 may be used for the high-speed transfer of voice, video, and alphanumeric data over atmospheric ranges with varying meteorological properties. In a preferred embodiment, the two channels in each hybrid link are bi-directional and are engineered to ensure that the combined transmission capability of the two channels will be operational at least at a certain minimum level, regardless of the varying weather conditions. Examples of percentage

levels of availability which are sometimes guaranteed by service providers in this industry include 99.995 percent (aka four 9's and a 5), and 99.999 percent (aka five 9's). However, in certain applications, much lower levels may be acceptable, such as 90 percent availability (aka one 9). In fair weather conditions, the hybrid link is engineered to support data burstability, or more specifically, a constant, high data rate connection which provides end-users with the impression that data being delivered from a network is being provided over a constant connection at high speed. In foul-weather (e.g., fog or intense rain) conditions, the two channels in each hybrid link are designed to implement a transmission scheme which is intended to ensure that priority data will always be transmitted over an operating channel.

FIGURE 5 shows the steps in a process 60 for using the hybrid link 10 to transmit data. As illustrated in FIGURE 5, at a block 62 the data subsets that are to be transmitted by the hybrid link are first determined. In one embodiment, the data subsets may be assembled into packets using one or more packetization protocols, some which may use statistical methods for timing the transmission and retransmission of data and acknowledgment packets.

Once the data subsets have been determined, at a decision block 64 the process determines whether a data subset is to be transmitted over both of the optical and non-optical channels. If the data subset is to be transmitted over both channels, the process proceeds to a block 68 where the data subset is transmitted. If the data subset is not to be transmitted over both channels, the process proceeds to a decision block 66.

At decision block 66, the process determines whether the data subset is to be transmitted over the optical channel. In a preferred embodiment, the decision process is the same as that used by Internet routers. Furthermore, the decision process may be based on emerging Internet standards, such as MPLS (multi-protocol label switching). If the data subset is to be transmitted over the optical channel, the process proceeds to a block 70 where the data subset is transmitted. If the data subset is not to be transmitted over the optical channel, the process proceeds to a block 72 where the data subset is transmitted over the non-optical channel. At a block 74, the data subsets are received from the optical and non-optical channels, in accordance with the transmissions from the blocks 68, 70, and 72.

In the parallel configuration used in each hybrid link 10, each channel is separately engineered to provide enough channel margin to overcome the attenuating

effects of the interactions between the electromagnetic waves transmitted on a given channel and the atmospheric media. Thus, hybrid links deployed in excessively rainy locations can be designed to ensure that the free-space optical communication channels have enough margin to carry a significant portion of the data, while hybrid links deployed in dense fog locations can be designed to ensure that the non-optical channels such as microwave or millimeter-wave channels have enough margin to carry a significant portion of the data. By engineering channel margins for known weather conditions, the overall cost of each hybrid link can be significantly reduced. Part of the cost savings comes from using the complementary nature of the optical and non-optical channels to avoid the need for the highly specialized components that would be required to implement a single channel system that could operate over the wide range of weather conditions by itself. In other words, the complementary nature of the hybrid link avoids the need to use specialized high-performance transmitters on each channel, each of which may have required adaptive power control. In addition, further cost savings are realized by eliminating the need for highly sensitive receivers which may have required the use of costly coding and error-correction schemes as well as specialized signal processing hardware for linearization and low-noise preamplification.

Data transmitted over one or more atmospheric ranges will ultimately be received at the switches or routers used by interim hybrid links or at some end-user device, such as a desktop personal computer, wireless telephone, or teleconferencing video display. Existing packet switching protocols may be used to ensure the successful retransmission of data received at interim hybrid links or the successful reassembly of data packets in one or more end-user devices. Hybrid links can be used to transmit voice, video, and alphanumeric data over point-to-point and point-to-multipoint architectures in a protocol independent fashion. A plurality of hybrid links can also be deployed to provide high-availability data transmission services in a wide range of network topologies, including rings, meshes, stars, trees, and hubs-and-spokes.

The operational performance of a hybrid link 10 depends in significant part on the weather conditions that exist during the transmissions. FIGURES 6A and 6B contain tables that tabulate loss data (in decibels/km) in four weather conditions (fog, excessive rain, heavy rain, and drizzle), for four exemplary frequencies (28 GHz microwave spectrum, 39 GHz microwave spectrum, 60 GHz millimeter-wave

spectrum, and 180 THz optical spectrum). These tables compile information from experimentally derived attenuation curves, which are readily available to those in the art. In the context of the present invention, fog data refers specifically to a visibility condition of 50 meters, which normally distinguishes "dense" and "thick" fog. Excessive rain data refers to a rainfall rate of 150 mm/hr (typical of tropical or semi-tropical regions such as Miami). Heavy rain data refers to rainfall rate of 25 mm/hr, and drizzle refers to precipitation rates of 0.25 mm/hr.

FIGURE 6A contains a table 80 which shows the rates of attenuation of carrier frequencies in four of the frequency bands that may be used for data transmission in the hybrid link 10. FIGURE 6B contains a table 100 which shows a similar set of attenuation rates that were determined from slightly different experimental data. The data points shown in the tables are intended to illustrate the effects of the varying weather conditions on the different frequency signals. The right-most four columns in these figures tabulate the relative advantage of optical over non-optical transmission at the specified frequencies under various weather conditions.

As an illustrative example of how the tables 80 and 100 are read, in FIGURE 6A, in the microwave band, signal attenuation at 28 GHz in excessive rain is shown to be at 23.7 decibels per kilometer. In the millimeter-wave band, signal attenuation at 39 GHz in excessive rain is 56.2 decibels per kilometer, while signal attenuation at 60 GHz in excessive rain is 55.43 decibels per kilometer. In the optical band, signal attenuation at 180 THz in excessive rain is 31.6 decibels per kilometer, somewhat higher attenuation than that for the 28 GHz microwave band, but less than that for the 39 GHz and 60 GHz millimeter-wave bands. The right-most four columns of tables 80 and 100 tabulate the relative advantage of optical over non-optical transmission at the specified frequencies under various weather conditions.

Notwithstanding their sometimes comparable and sometimes favorable rates of attenuation, in excessive rain optical frequencies are preferred over 28 GHz microwave frequencies for data stream transmission due to advantageous economies of scale and the significantly greater information carrying capacity of optical beams. With respect to existing economies of scale, the design, construction and manufacturing of optical frequency channels with large channel margins has been significantly simplified by the widespread availability of economical components for optical frequency transmitters and receivers. The inherently wide bandwidth of optical frequency channels permits

vast amounts of data to be transmitted at significantly higher data rates than those available in the microwave or millimeter-wave frequency ranges. The existence of economical optical components and the inherent wide bandwidth of optical frequency channels can significantly reduce the performance requirements of custom-designed wide-dynamic range receivers for use on highly regulated microwave frequencies. As a result, optical frequency channels can provide a significant economic advantage over microwave frequency channels in rain conditions generally, and excessive rain conditions in particular.

However, optical frequencies suffer considerably greater attenuation in fog when compared to the rate of attenuation of either millimeter-wave frequencies or microwave frequencies, and therefore tend to be preferred for data transmission in rain. Optical frequencies tend to suffer greater attenuation in fog than in rain because the radius of fog droplets (5 to 15 μm) is of the order of laser wavelengths, while the radius of rain droplets tends to be considerably larger, typically in the range from 200 μm to 2000 μm. However, microwave and millimeter-wave frequencies tend to be more significantly attenuated by the larger sized rain droplets since the droplets tend to be on the order of the wavelengths of these frequencies. Thus, microwave and millimeter-wave frequencies are preferred for data transmission in fog. Millimeter-wave frequencies provide somewhat higher data rates than microwave frequencies, but such frequencies are not capable of propagating as far as microwave frequencies in comparable weather conditions. Hence, microwave frequencies are preferred over millimeter-wave frequencies in fog conditions for the transmission of data over longer distances.

The frequencies that are shown in FIGURES 6A and 6B exhibit rates of attenuation that affect the operational performance of the hybrid link 10. More particularly, the frequencies in the microwave range (1 GHz to 30 GHz) and millimeter-wave range (30 GHz to 300 GHz) tend to be more significantly attenuated in rain than in fog. In contrast, carrier frequencies that are greater than or equal to 100 THz are more highly attenuated in foggy weather conditions than in rain.

One aspect in the design of hybrid link 10 is the incorporation of a sufficient amount of margin for each of the channels. As discussed earlier, a hybrid link 10 is comprised of a free space optical communication channel and a non-optical channel. In some circumstances, each of these channels may be referenced as a separate

communication link. An additional important aspect of the design of hybrid link 10 is its use to extend or stretch the distance over which a channel operating on a particular frequency in a particular weather condition may transmit. More specifically, the hybrid link 10 is designed to stretch the length of the optical channel by designing the link implementing the non-optical channel with enough link margin to overcome the attenuating effects of fog particles on the transmission path that would otherwise greatly attenuate a link operating solely on an optical frequency. In this particular case, the hybrid link 10 would be designed with sufficient link margin, or transmission power, on the non-optical channel to transmit a significant amount of the data in foggy weather conditions. Likewise, the hybrid link 10 would be designed with sufficient link margin on the optical communication channel to transmit a significant amount of the data in rainy weather conditions.

By extending the distance over which the channels may transmit, the distance between the transmitters and receivers may be increased. Thus, with reference to FIGURE 1, the length L of the hybrid link 10 may be increased. This is particularly advantageous when the transmitting and receiving components must be placed on rooftops or in similar locations.

The result of designing specialized versions of hybrid link 10 is the extension, or "stretching," of a channel that would otherwise be severely attenuated if used alone. By modifying link margins based on prior knowledge of prevailing weather conditions in the region(s) in which hybrid links will be deployed and the rates at which commercially important electromagnetic signals are attenuated, hybrid links 10 can be custom designed with sufficient link margin to ensure successful, high speed data transmission in varying weather conditions.

Information such as that shown in FIGURES 6A and 6B (Signal Loss Rates) and readily available Signal Frequency vs. Signal Attenuation charts is used to determine the extent to which a particular channel can be extended or "stretched." The charts included in these figures are used to design optical, microwave, and millimeter-wave channels with complementary performance characteristics under widely-varying weather conditions. In one embodiment, rather than designing a single-band link with a link margin large enough to accommodate all-weather conditions across some pre-defined range, each link is designed independently. Then each link is mutually-

optimized such that together they can operate over a longer range with higher availability than either link could operate on its own.

The two links are then combined in a manner that enables a customer served by the link to experience high "burstability" in fair weather conditions, along with a guaranteed high level of availability for priority traffic in all-weather conditions. "Burstability" is a feature of an internet connection that provides internet surfers with rapid response times such as are typical of a high data rate connection. Internet access connections made with hybrid links 10 can be marketed by selling customers a minimum guaranteed bit rate sufficiently broad to handle all of their priority traffic, while also providing fair-weather "burstability" at a service level supported by a combination of hybrid links.

The following examples demonstrate how the combination of a microwave channel and a free space optical channel can stretch the range of wireless communications links. In particular, the following two combinations will be discussed: (i) the use of microwaves to stretch the range of optical links in heavy fog, and (ii) the use of optical links to stretch the range of microwave links in heavy rain. In general, the larger a system's link margin, the more it costs. Telecommunication systems with large link margins tend to be more expensive to build for the following reasons: (1) they tend to require more powerful transmitters (possibly with adaptive power control), and (2) they tend to use more sensitive receivers (often using expensive coding schemes, error correction schemes, low noise preamplifiers, and other costly applications of linearization engineering techniques). A goal of the present invention is to engineer a hybrid link having a combined link margin designed to function reliably in varying weather conditions, while minimizing the margin requirements on the separate links.

The signal attenuation experienced by microwave links in heavy rain has been combined with meteorological rainfall data and incorporated into at least two operating models for fixed-wireless communication systems. If it existed, an analogous model for wireless optics would combine data on the attenuation of light in varying levels of fog with meteorological data on the temporal and spatial distribution of fog density around the world. Although such a model could be developed to predict the effects of scintillation on wireless optical systems based on meteorological temperature data, its usefulness would be greatly limited since scintillation is extremely sensitive to and

greatly affected by the presence of man-made formations, such as concrete, which may be on or proximate to the optical transmission paths.

The relative transparency of rain at optical frequencies enables a hybrid link to be deployed that will operate over a longer range in excessive rain than would a microwave link used alone. By using the link extending property of the hybrid link 10, a specialized hybrid link 10 may be designed for a region that frequently suffers excessive rain. For illustrative purposes, a hybrid link design will be developed for a region that never suffers from fog. Since the design is for a region that never suffers from fog, it will not be necessary to consider fog attenuation data in the design of the optical link margin.

Attenuation of microwaves in rain becomes increasingly severe as frequency increases from 28 to 39 to 60 GHz. The increased rate of attenuation with frequency occurs primarily because the wavelength of the microwaves approaches the size of the raindrops, and, as a result, the scattering of the microwaves off the raindrops causes them to become increasingly diffuse. This is a phenomena referred to as Mie scattering. Mie scattering affects microwaves in a manner similar to way fog affects optical beams, and explains why the attenuating effect of excessive rain on microwaves lessens as signal frequencies increase beyond approximately 70 GHz.

In contrast, the attenuation of optical beams by excessive rain is approximately between 28 and 31.6 decibels/km, as illustrated, for example, in FIGURES 6A and 6B. In practical effect, the data indicates that optical beams penetrate rain more effectively than do microwave beams. Further, while the atmospheric attenuation at frequencies below about 30 GHz is less than or comparable to the atmospheric attenuation of optical beams, the optical beams maintain a clear advantage over 39 GHz and 60 GHz microwaves when it comes to penetrating excessive rain.

Rather than budgeting for the full microwave loss across a particular link range, a hybrid system can eliminate from its link budget the margin normally assigned to rain (thus economizing substantially on the microwave link costs), by relying on the optical portion of the system to handle data transmission through the rain. This results in substantial cost advantages for two reasons. First, because the atmospheric attenuation due to rain at optical frequencies tends to be less than at microwave frequencies (particularly at 39 GHz and at 60 GHz, where optics affords a 10 to 25 decibels/km advantage over microwaves, as shown, for example, in FIGURES 6A and 6B). Second,

the economies of scale in optical technologies make it simpler and more cost-effective to build a larger link margin into an optical link rather than into a microwave link.

The factors considered for the design of a hybrid microwave-optical link in which the microwave channel frequency is 39 GHz will illustrate how the design methodology is to be applied. First, assume a design for a hybrid link is to be developed for data transmission over a 1 km range with high availability (e.g., approaching 99.999%, or "five-9's"). Based on an attenuation rate of 56.2 decibels/km indicated by the data shown in FIGURES 6A and 7A, a 39 GHz link would have to incorporate a link margin of 56.2 decibels to maintain a high level of performance in excessive rain. A link margin nearly this large might be required to avoid receiver saturation, maintain the dynamic range necessary for the level of modulation to be deployed (e.g., 256 Quadrature Amplitude Modulation (QAM)), and to minimize deleterious interference effects under clear-weather conditions. Although millimeter-wave link margins this large are not unheard of in advanced radar systems, engineering challenges associated with their design and construction make their deployment economically impractical.

Consider now the design of an optical link for hybrid deployment in parallel with a microwave link with reference to FIGURE 6A. Since the atmospheric attenuation of the optical beam in excessive rain is 31.6 decibels/km, the optical link would have to be designed to provide a link margin of 31.6 decibels on a 1 km link. Link margin refers generally to the range of powers over which the transmitter and receiver on a particular communication link can be made to work. The example presented above demonstrates how a microwave link, without any budget for rain, can be "stretched" to about 1 km by integrating it into a hybrid microwave-optical system in which the optical channel of a hybrid link is designed to include a margin for signal attenuation due to excessive rain.

The system design presented above also shows that free space optics provides a 24.6 decibel advantage over 39 GHz microwaves in the presence of excessive rain. Moreover, the design, construction and economical manufacturing of large optical link margins is greatly simplified by the following two factors: (i) the availability of relatively inexpensive optical components, and (ii) the intrinsically wide optical communications bandwidth. Both factors greatly obviate the need to use the expensive

wide dynamic range receivers for robust performance on highly regulated microwave frequencies.

While the above example describes a hybrid link designed for use in heavy rain, similar principles can be applied for designing a hybrid link for use in heavy fog. A hybrid link 10 will operate over a longer range in heavy fog than would an optical link alone. Some geographic regions rarely, if ever, receive excessive rain but suffer more frequently from "dense fog" where typical visibility is between zero and fifty meters. In the design of this type of link, the link margin for excessive rain would not be a primary factor. Instead, the key issue would be budgeting sufficient margin for dense fog.

The atmospheric attenuation data provided in FIGURES 6A and 6B would again be used as the basis for the design of a hybrid link. As noted in these figures, the attenuation rate of an optical frequency signal due to "dense fog" is not less than 205 decibels/km, which corresponds to a fog condition having an associated visibility of 50 meters. The attenuation rate is greater in locations where the visibility is considerably lower. At present, it is impractical to build optical links with margins greater than about 40 decibels and, thus, in such weather conditions the range of an all-optical link would be limited to about 195 meters (or 127 meters for visibilities less than 50 meters associated with atmospheric attenuations of 315 decibels/km). Since fog is essentially transparent to microwaves (i.e., less than 1 decibel/km attenuation at all microwave frequencies), the deployment of a hybrid optical-microwave link would permit the performance of the combined system to be extended or "stretched" to the desired 1 km design range which was originally targeted.

The examples discussed above considered two ideal cases to demonstrate that the deployment of hybrid optical-microwave links can effectively extend the range of high bandwidth wireless links in those regions of the world that experience excessive rain and fog conditions. Although such weather conditions occur in some commercially important geographical markets (e.g., Miami (excessive rain), San Francisco, or Seattle (occasional dense fog)), many more commercially important regions experience less severe weather variations. For more typical regions experiencing moderate amounts of both rain and fog, a hybrid link can be designed with a longer range than either link would exhibit if operated independently. The design of a hybrid link 10 for the particular weather condition should take into account

the occasional presence of both fog and rain. The density of fog and the rates of rainfall may vary continuously over a wide range between zero and the excessive (dense) levels.

In the most general case, the probability of occurrence of rain at a level L_i can be represented by the variable $P_r(L_i)$; and the probability of occurrence of fog at a level L_j can be represented by the variable $P_f(L_j)$. Given this a priori information, the link margins of the separate optical and microwave links can be optimized as follows: enough margin is budgeted in the optical link to accommodate the worst rain conditions, and enough margin is budgeted in the microwave link to accommodate the worst fog conditions. By using this margin allocation scheme, the various weather scenarios can be properly addressed.

The link-stretching property of the hybrid link 10 can be used advantageously even when designing a link for a region which suffers from both excessive rain and dense fog. In such situations, the microwave link is designed with enough link margin to penetrate the fog (this level of microwave attenuation can be accommodated by less than a decibel per km in the microwave link budget), and the optical link can be designed with enough link margin to penetrate the rain. Substantial link margin savings will be achieved if the non-optical link is running at either 39 or 60 GHz. When the non-optical link is at 28 GHz, the advantage associated with using optics rather than microwaves to penetrate the rain generally comes about from the economies of scale associated with optics rather than from the physics of atmospheric propagation.

Although several different strategies can be used to handle the aggregation and priority queuing of the data packets containing the information being sent across the microwave and optical links, a preferred embodiment would use both the microwave and optical links to provide the user of a point-to-point system with "burstability" under fair-weather conditions. This "burstability" characteristic could be provided by delivering data at a data rate two or more times higher than the minimum level of service provided in a standard service level agreement between consumer and service provider. A service level agreement sets forth the minimum level of telecommunication service that will be guaranteed to be delivered by a telecommunication service provider to a customer.

As an example, in the embodiment of FIGURE 1 where the switching devices 16 and 18 are responsible for splitting and combining data streams, the switching

devices 16 and 18 would be used for the aggregation and priority queuing of telecommunication data. In the event that one of the two links was disrupted, the switching devices 16 and 18 would use industry-standard prioritization schemes to prioritize voice and video over data downloads and general-purpose web-surfing. In one embodiment, commercial off-the-shelf subsystems could be connected together to accomplish this function, or a custom switch could be designed and built to handle the aggregation of a minimum of two data streams at data rates specific to the microwave and optical links shown in FIGURES 6A and 6B. In a preferred embodiment of the present invention, current microwave links operate at data rates consistent with the OC-3 standard (155 Mbps), but can be expected to deliver data at rates consistent with the OC-12 (622 Mbps) and GbE standards, and possibly considerably higher for 60 GHz links.

Although the discussion presented above has focused in some detail on how the present invention would work in a point-to-point architecture, a plurality of hybrid links 10 can be combined and used as elements of more complex architectures including meshes, rings, hubs-and-spokes, stars, and in other architectures well known by those in the art. Moreover, although the discussion presented above described in detail how a hybrid link could be designed to provide mutual linear protection for data transmitted on both channels (i.e., data transmitted on the optical channel can be protected by transmitting data on the microwave channel in fog conditions, and data transmitted on the microwave channel can be protected by transmitting data on the optical channel in rainy conditions), the invention can also be applied in other architectures providing greater protection for data such as rings and meshes..

The method presented above for extending the range of optical links via the hybrid deployment of microwaves in parallel with high bandwidth free-space optical links affords a powerful advantage to mesh-based wireless systems; namely, that it extends the maximum allowable distance between nodes. In particular, using extended hybrid links in mesh architectures permits the intermixing of all-optical links and all-microwave links when and where necessary to optimize system performance and to minimize overall system cost. For example, an architect of a hybrid microwave-optical mesh might choose to deploy an all-microwave link between two distant buildings that are normally separated from each other by heavy fog (e.g., perhaps two buildings whose line-of-sight is right near sea level straight across a foggy ocean waterfront).

Likewise, it may be advantageous to deploy an all-optical link between two spots that are typically above the fog or in areas usually drenched in rain, and reserving the hybrid microwave-optical link for use between two sites that have especially problematic fog-rain-range constraints. Multiple short optical hops might be used as an all-optical "tunnel" through most fog conditions, while a longer-range all-microwave link in the architecture could be used to handle priority traffic in extreme fog. Optical fibers could likewise be knitted into the mesh to provide connectivity over longer distances or underneath line-of-site obstructions. In one embodiment, the hybrid link 10 can be used in a mesh architecture using Internet Protocol (IP) or MPLS (Multi-protocol Label Switching) or MPLS (Multi-Protocol Lambda Switching) to handle the routing and priority queuing.

The hybrid link 10 can also be used in a ring architecture having multiple nodes to enhance the ability of such an architecture to transmit data in all weather conditions while providing maximum protection for all transmitted data. By including one or more "point-to-consecutive-point" hybrid links 10 in a ring architecture, the overall distance covered by such an architecture can be increased due to the ability to extend or "stretch" the length of each hybrid link between one or more pairs of nodes, where each such link consists of a free space optical channel combined with a non-optical channel which transmits data on either a microwave or millimeter-wave frequency. Since the hybrid link can transmit data independent of any particular data transmission protocol, a great variety of data transmission protocols can be used to enhance the overall protection for the data transmitted through a selected ring architecture. Such architectures are referred to as "ring protected architectures" by those skilled in the art since they employ data transmission protocols which enhance the overall data protective capabilities of these architectures. The use of one or more hybrid links greatly enhances the protective capabilities of such architectures.

In one embodiment, the hybrid link 10 can be used in a ring architecture using Synchronous Optical NETwork technology, referred to as SONET. The architecture uses a specialized pair of switching devices for the switches 16 and 18, referred to as SONET ADMs (SONET Add-Drop Multiplexers), for data transmission and data routing. The SONET technology can be applied using wireline and wireless networking technology. In the present embodiment it is used in a wireless combination to facilitate the use of one or more hybrid links 10. A SONET ring architecture

including hybrid links 10 will enable the inter-node separations of the wireless SONET ring to be extended in a manner consistent with the use of the hybrid links 10 while also supporting industry standards for a uni-directional path switched ring (UPSR), a bi-directional line switched ring (BLSR), or line protection. By using the hybrid link 10 in a ring architecture, the optical channel will be protected by the microwave channel and the microwave channel will be protected by the optical channel, ensuring that both links will be mutually protected. It should be understood that another non-optical channel such as a millimeter-wave channel may be used in place of the microwave channel in the ring architecture, depending on applicable system performance requirements established by those skilled in the art. In yet another embodiment, optical fibers can be serially interworked with the microwave and optical links.

During data transmission in a SONET-based (or SDH-based) ring architecture, in the event the optical link is impaired or becomes disabled by heavy fog, the SONET ADMs, used as switching devices 16 and 18, automatically re-route traffic in the opposite direction over the microwave channel of the ring with a protection-switching time of less than 50 milliseconds. Similarly, should the microwave link become disabled by excessive rains, the SONET ring will automatically re-route traffic over the optical link (again, with a protection switching time of less than 50 milliseconds) using the SONET ADMs as the switching devices 16 and 18. In fair-weather conditions, the bi-directional line-switched protection protocol enables the simultaneous transmission of data on both links in the same or opposite directions, as known by those skilled in the art.

While the preferred embodiment of the invention has been illustrated and described, it will be appreciated that various changes can be made therein without departing from the spirit and scope of the invention.

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The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A communication system for use in varying weather conditions, comprising:

an optical wireless communication channel comprising a first transmit unit, said first transmit unit transmitting a first data signal in an optical frequency range;

a non-optical wireless communication channel comprising a second transmit unit, said second transmit unit transmitting a second data signal in a non-optical frequency range;

the optical and non-optical communication channels being coupled in parallel and at times both transmitting data simultaneously.

2. The communication system of Claim 1, wherein the communication system communicates a set of data, the data being routed to the optical and non-optical channels such that a first subset of the data is communicated across the optical channel and a second subset of the data is communicated across the non-optical channel.

3. The communication system of Claim 2, wherein the first subset of data contains different data than the second subset of data.

4. The communication system of Claim 2, wherein for current weather conditions the system determines the individual carrying capacities of the optical and non-optical channels.

5. The communication system of Claim 4, wherein the system routes data to the optical channel and the non-optical channel in accordance with their individual carrying capacities.

6. The communication system of Claim 1, wherein the non-optical frequency range of the non-optical channel has a known attenuation curve over varying weather conditions, such that in fog with a visibility of 50 meters the attenuation of the second data signal is significantly less than the attenuation of the first data signal.

7. The communication system of Claim 6, wherein in fog with a visibility of 50 meters, the attenuation of the second data signal is 20 dB less than the attenuation of the first data signal.

8. The communication system of Claim 1, wherein the non-optical channel transmits the second data signal in a microwave frequency range.

9. The communication system of Claim 1, wherein the non-optical channel transmits the second data signal in a millimeter wave frequency range.

10. The communication system of Claim 1, wherein the channel margins of the optical and non-optical channels are selected so as to provide a high statistical availability for a preselected data transmission rate of the system.

11. The communication system of Claim 10, wherein the statistical availability of the data rate is at least 90 percent.

12. The communication system of Claim 10, wherein the statistical availability of the data rate is at least 99.995 percent.

13. The communication system of Claim 10, wherein the statistical availability of the data rate is at least 99.999 percent.

14. The communication system of Claim 1, wherein in clear weather conditions the optical channel transmits the first data signal at a first data rate and the non-optical channel transmits the second data signal at a second data rate, the second data rate being more than a negligible percentage of the first data rate.

15. The communication system of Claim 14, wherein the second data rate is at least 10 percent of the first data rate.

16. The communication system of Claim 1, wherein the optical channel is constructed to be able to transmit at a data rate of at least approximately 10 billion bits per second, and the non-optical channel is constructed to be able to transmit at a data rate of at least approximately 300 million bits per second.

17. The communication system of Claim 16, wherein the non-optical channel has the capacity to be able to transmit at a data rate of 1 billion bits per second.

18. The communication system of Claim 1, wherein the optical channel is constructed to be able to transmit at a data rate of at least approximately 1 billion bits per second, and the non-optical channel is constructed to be able to transmit at a data rate of at least approximately 100 million bits per second.

19. The communication system of Claim 1, wherein the optical channel is constructed to be able to transmit at a data rate according to at least the OC-12 standard, while the non-optical channel is constructed to be able to transmit at a data rate according to at least the OC-3 standard.

20. The communication system of Claim 1, wherein the optical channel is constructed to be able to transmit at a data rate according to at least the OC-48 standard, while the non-optical channel is constructed to be able to transmit at a data rate according to at least the OC-12 standard.

21. The communication system of Claim 1, wherein the optical channel is constructed to be able to transmit at a data rate according to at least the OC-192 standard, while the non-optical channel is constructed to be able to transmit at a data rate of at least approximately 1 billion bits per second.

22. The communication system of Claim 1, further comprising a first network and a second network, the first network being the source of the first data signal and the second data signal, the second network receiving the first data signal and the second data signal after they are transmitted over the optical and non-optical communication channels.

23. The communication system of Claim 22, wherein the first network represents a global network, while the second network is a private network at a user's facility.

24. The communication system of Claim 22, wherein the first network is a global terrestrial network, while the second network is an extraterrestrial or satellite-based network.

25. In a wireless communication system, the communication system having an optical wireless communication channel, the optical channel comprising a first transmit unit and a first receive unit, wherein when the first transmit unit and the first receive unit are separated by a first distance the optical channel provides communication at a first data rate, the improvement comprising:

coupling a non-optical wireless communication channel in parallel with the optical channel, the non-optical channel increasing the effective range of the communication system such that when the first transmit unit and the first receive unit are separated by a second distance that is greater than the first distance, the combined data communication of the non-optical channel and the optical channel is sufficient to maintain the communication of the system at the first data rate.

26. The improvement of Claim 25, wherein when the system is operating in fog with a visibility of 50 meters, the percentage of the overall system data rate that is carried by the non-optical channel is significantly increased from the percentage that is carried by the non-optical channel in clear weather conditions.

27. A method for increasing the range of a communication system, the communication system including an optical wireless communication channel, the method comprising:

coupling a non-optical wireless communication channel in parallel with the optical wireless communication channel; and

transmitting a first data signal over the optical wireless communication channel and a second data signal over the non-optical wireless communication channel.

28. The method of Claim 27, wherein the non-optical channel transmits the second data signal at a frequency range which has a known attenuation curve over varying weather conditions such that in fog with a visibility of 50 meters the attenuation of the second data signal is significantly less than the attenuation of the first data signal.

29. The method of Claim 27, wherein the first data signal comprises different data than the second data signal.

30. The method of Claim 27, further comprising determining the individual carrying capacities of the optical wireless communication channel and the

non-optical wireless communication channel under a set of weather conditions, and adjusting the amount of data in the first and second data signals in accordance with the individual carrying capacities of the channels.

31. A wireless communication system for transmitting data streams at high frequencies in varying weather conditions, comprising:

a first switching device having a first output, a second output, and an input coupled to a first network;

a first wireless communication channel for transmitting data streams within a first range of frequencies, the first communication channel comprising a first transmit unit and a first receive unit, the first transmit unit coupled to the first output of the first switching device;

a second wireless communication channel for transmitting data streams within a second range of frequencies, the second communication channel comprising a second transmit unit and a second receive unit, the second transmit unit coupled to the second output of the first switching device;

a second switching device having a first input, a second input, and an output coupled to a second network, the first input coupled to the first receive unit of the first communication channel, the second input coupled to the second receive unit of the second communication channel;

the frequency ranges of the first and second communication channels being such that under foggy conditions, the data streams of the second communication channel will be significantly less attenuated than the data streams of the first communication channel, the first and second communication channels at times transmitting data streams at the same time.

32. The communication system of Claim 31, wherein the first range of frequencies for transmitting data streams on the first communication channel is equal to or greater than 100 terahertz.

33. The communication system of Claim 31, wherein the second range of frequencies for transmitting data streams on the second communication channel is between 1 and 300 gigahertz.

34. The communication system of Claim 31, wherein the first communication channel is deployed in parallel to the second communication channel.

35. The communication system of Claim 31, wherein the first communication channel transmits data streams at a first data rate and the second communication channel transmits data streams at a second data rate, the second data rate being at least a non-negligible percent of the first data rate.

36. The communication system of Claim 35, wherein in clear weather conditions the second data rate is equal to the first data rate.

37. The communication system of Claim 35, wherein in clear weather conditions the second data rate is at least 10 percent of the first data rate.

38. A method of transmitting data streams at high frequencies in varying weather conditions, comprising:

determining a set of data to be transmitted over a communications link, the communications link comprising a parallel combination of an optical wireless communication channel and a non-optical wireless communication channel;

transmitting the set of data over the communications link, the transmissions across the optical channel and the non-optical channel being such that neither channel is used as merely a backup for the other.

39. The method of Claim 38, wherein the optical communications channel transmits in a frequency range that is equal to or greater than 100 terahertz.

40. The method of Claim 38, wherein the non-optical communication channel transmits in a frequency range that is between 1 and 300 gigahertz.

41. The method of Claim 40, wherein the non-optical communication channel transmits at a frequency of at least approximately 24 gigahertz.

42. The method of Claim 40, wherein the non-optical communication channel transmits at a frequency of at least approximately 27.5 gigahertz.

43. The method of Claim 40, wherein the non-optical communication channel transmits at a frequency of at least approximately 38.5 gigahertz.

44. The method of Claim 40, wherein the non-optical communication channel transmits at a frequency of at least approximately 60 gigahertz.

45. A method of using a hybrid link for the high speed transfer of data, comprising:

assembling a plurality of data packets in a first switching device;

transmitting the plurality of the data packets over first and second channels, the first and second channels transmitting signals at different frequencies such that in heavy fog the signals from the first channel will suffer significantly higher attenuation than the signals from the second channel;

receiving at a second switching device the plurality of data packets transmitted by the first and second channels; and

reassembling the plurality of data packets at the second switching device.

46. The method of Claim 45, wherein the hybrid link is part of a mesh-based architecture.

47. The method of Claim 45, wherein the routing of the data packets is accomplished via multi-protocol lambda switching.

48. The method of Claim 45, wherein the routing of the data packets is accomplished via multi-protocol label switching.

49. The method of Claim 45, wherein the hybrid link is part of a ring-based architecture.

50. The method of Claim 45, wherein the hybrid link is operated as a ring using industry-standard synchronous protection protocols such as SONET or SDH to accomplish the protection.

51. The method of Claim 50, wherein the synchronous protection protocol is unidirectional path-switched ring.

52. The method of Claim 50, wherein the synchronous protection protocol is bi-directional line-switched ring.

53. A method of transmitting data using a hybrid wireless communication link, comprising:

transmitting data over an optical wireless communication channel;

transmitting data over a non-optical wireless communication channel coupled in parallel with the optical wireless communication channel;

accumulating weather-related statistical data in regard to the geographic area in which the optical and non-optical channels are carrying the data;

determining channel margins necessary to obtain a predetermined percent availability of a preselected data rate for the hybrid link based on the statistical weather information that is accumulated.

54. The method of Claim 53, wherein the attenuation of the data signal carried by the non-optical channel is significantly less in foggy conditions than the attenuation of the data signal carried by the optical channel.

55. The method of Claim 54, wherein the channel margin for the optical channel is determined such that the non-optical channel will carry a significant proportion of the data in foggy conditions.

56. A method of providing fixed wireless Internet service, comprising:

transmitting data over an optical wireless communication channel, the transmission data rate of the optical channel being at a first level in clear weather conditions and at a second level in rainy weather conditions;

transmitting data over a non-optical wireless communication channel, the transmission data rate of the non-optical channel being at a first level in clear weather conditions and a second level in foggy weather conditions;

guaranteeing a minimum level of service to customers in clear weather conditions at a data rate that is based on the summation of the first levels of data rates of the optical and non-optical channels; and

guaranteeing a minimum level of service to customers in all-weather conditions at a data rate that is based on the smaller of the second levels of data rates of the optical and non-optical channels.

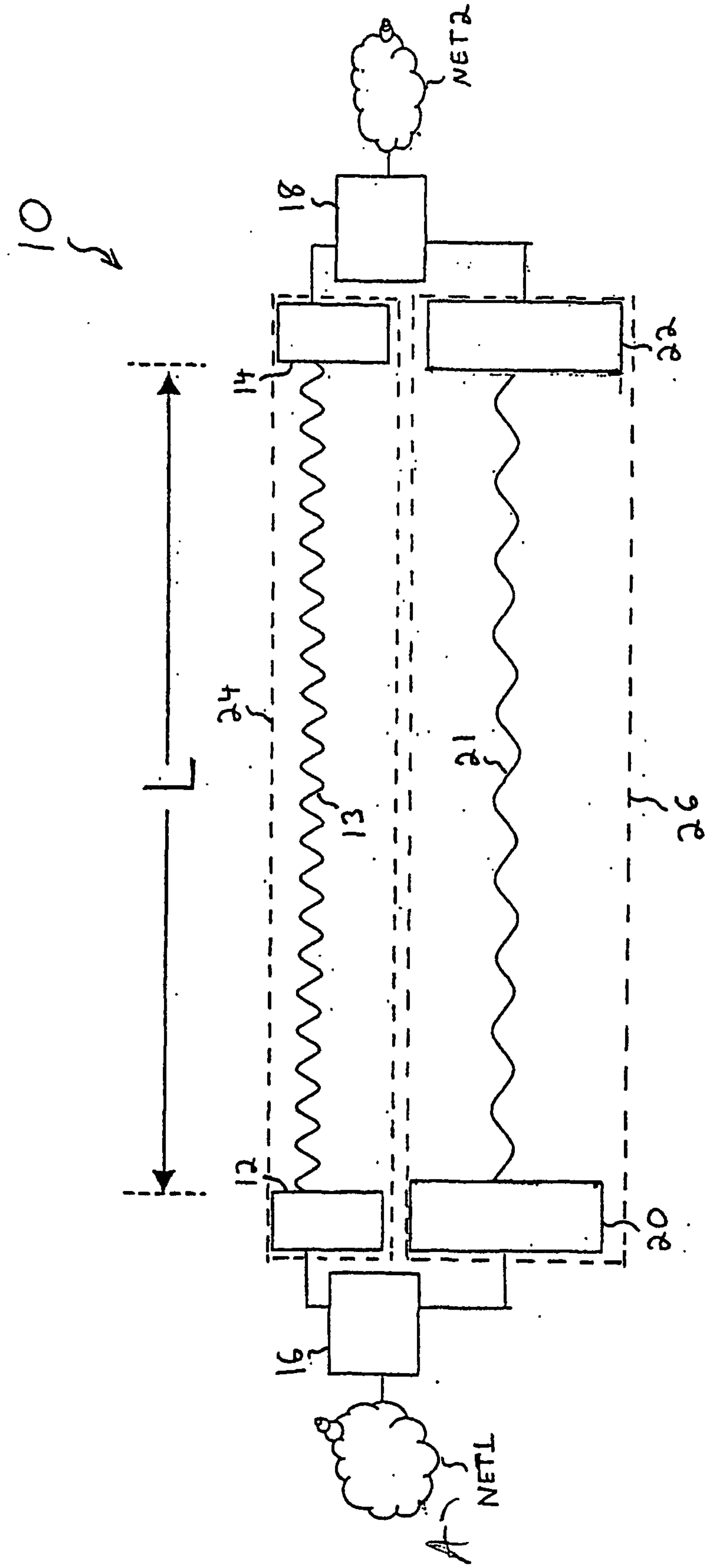

FIGURE 1

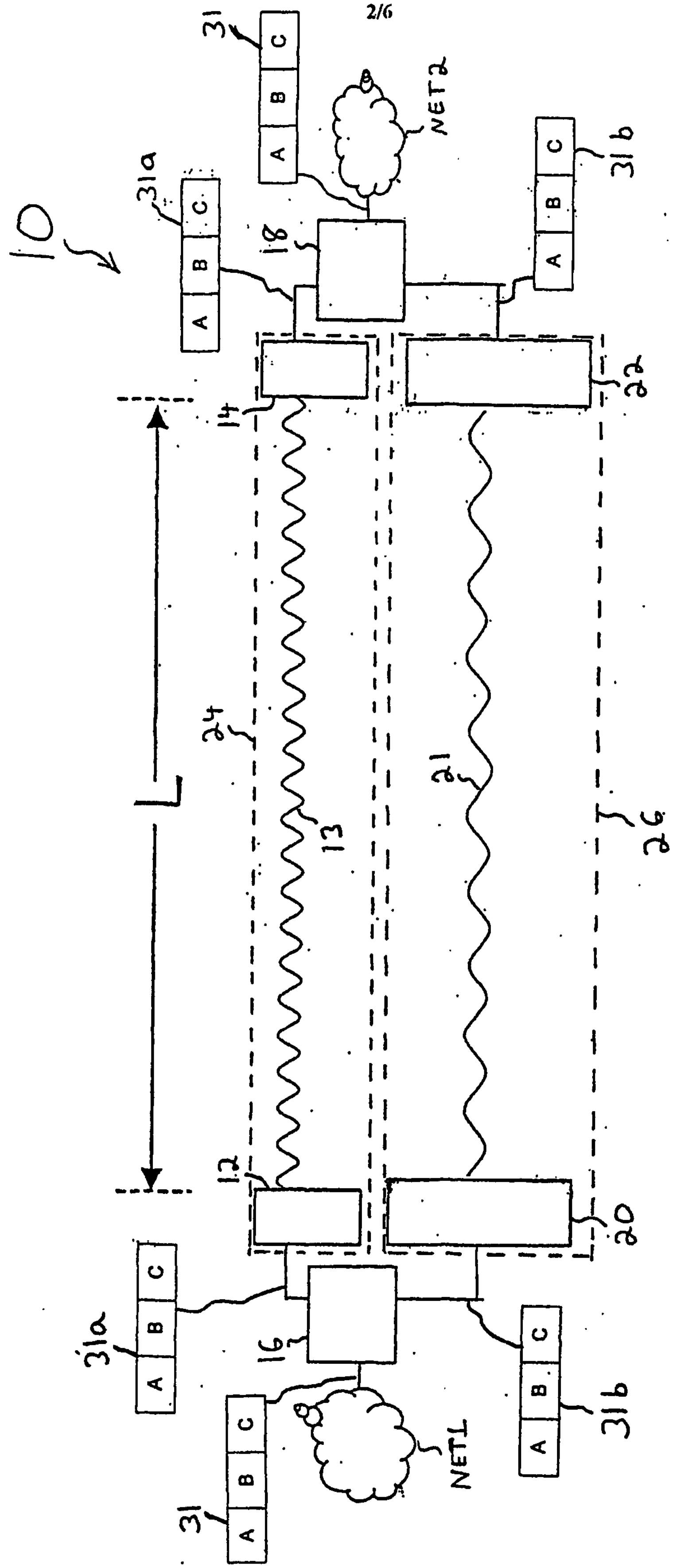

FIGURE 2

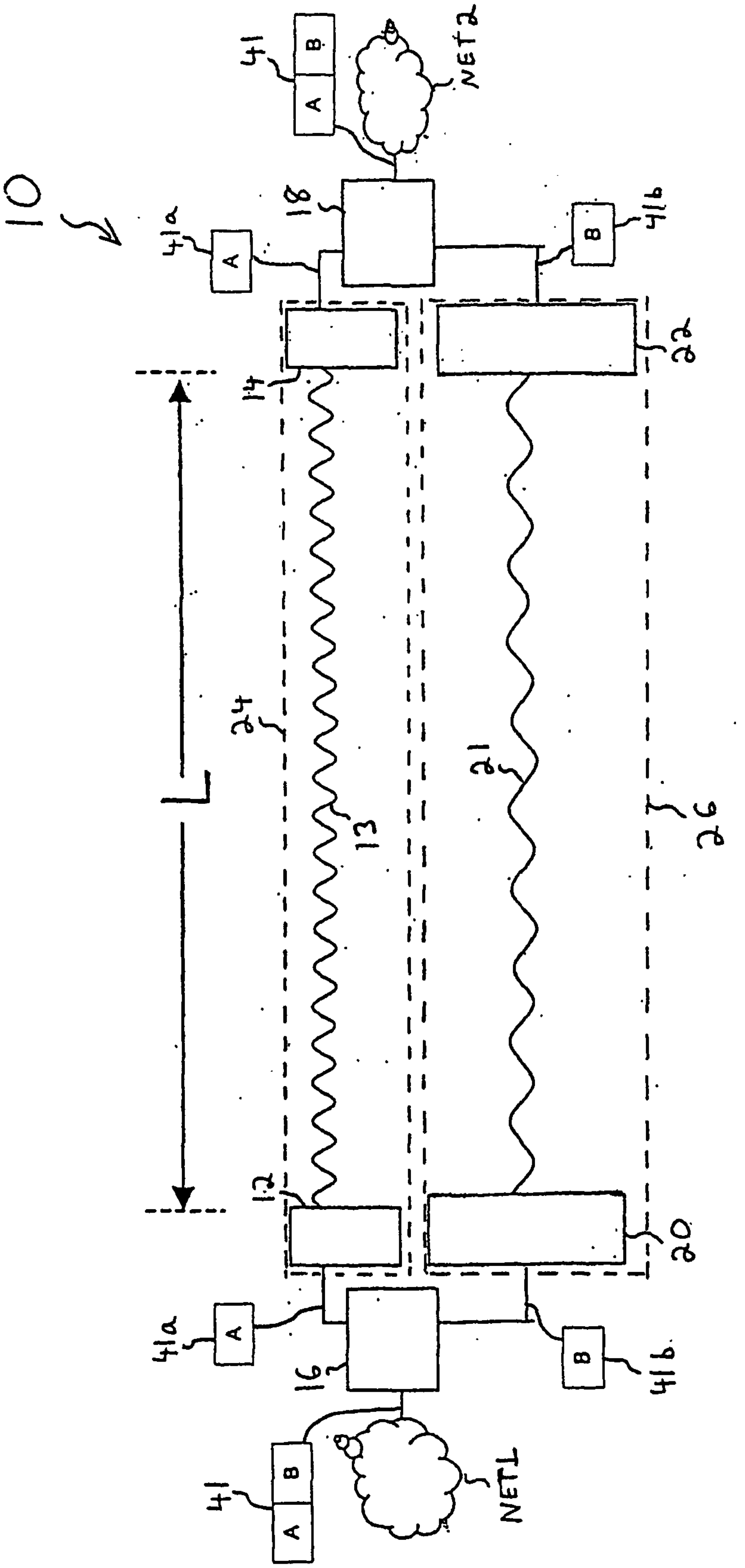

FIGURE 3

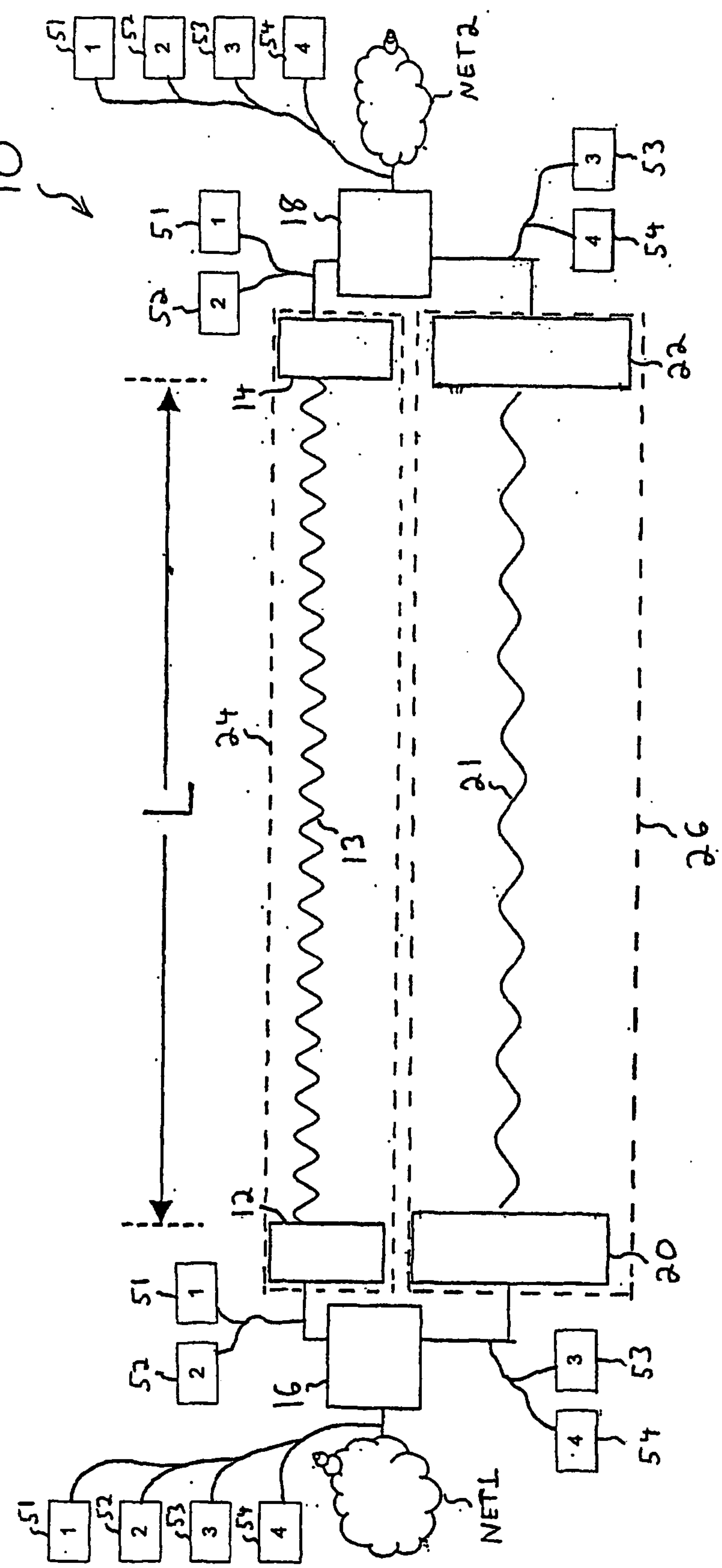

FIGURE 4

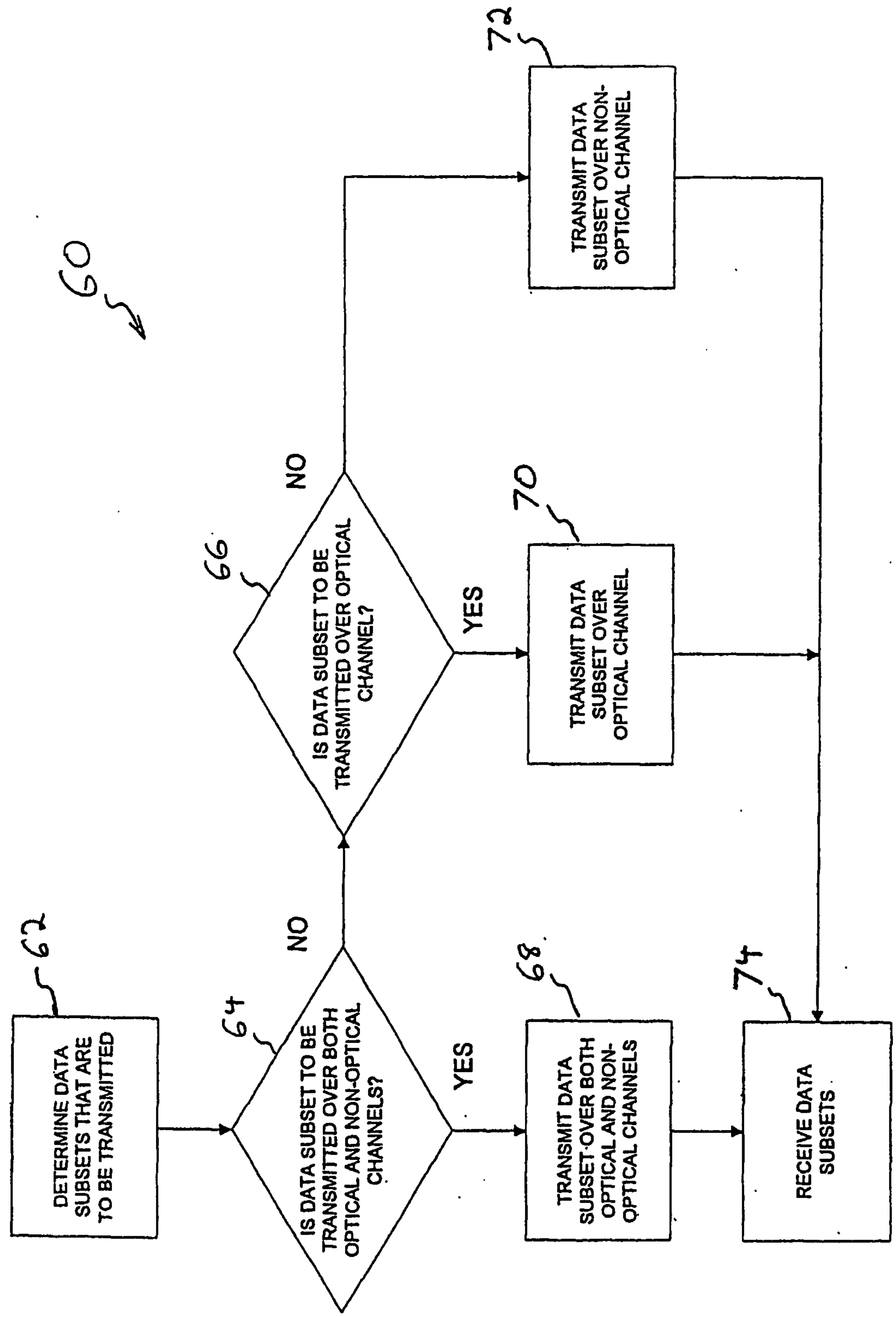
60
62
DETERMINE DATA SUBSETS THAT ARE TO BE TRANSMITTED
64
IS DATA SUBSET TO BE TRANSMITTED OVER BOTH OPTICAL AND NON-OPTICAL CHANNELS?
YES
NO
68
TRANSMIT DATA SUBSET OVER BOTH OPTICAL AND NON-OPTICAL CHANNELS
66
IS DATA SUBSET TO BE TRANSMITTED OVER OPTICAL CHANNEL?
YES
NO
70
TRANSMIT DATA SUBSET OVER OPTICAL CHANNEL
72
TRANSMIT DATA SUBSET OVER NON-OPTICAL CHANNEL
74
RECEIVE DATA SUBSETS

FIGURE 5

80

	Loss (dB/km) based on TRW chart					delta loss (mw-opt) (minus means optics pays bigger penalty)			
frequency	Fog Visibility 50 m (0.1 g/m^3)	Excessive Rain (150 mm/hr)	Heavy Rain (25 mm/hr)	Drizzle (0.25 mm/hr)		fog penalty	ER penalty	HR penalty	Drizzle penalty
28 GHz	0.49	23.70	3.20	0.03		-204.51	-7.90	-4.30	-0.36
39 GHz	0.10	56.20	5.60	0.07		-204.90	24.60	-1.90	-0.33
60 GHz	0.03	55.43	10.00	0.14		-204.97	23.83	2.50	-0.25
180 THz	205.00	31.60	7.50	0.39					

FIGURE 6A

100

	Loss (dB/km) based on Agilent chart and Astroterra paper					delta loss (mw-opt) (minus means optics pays bigger penalty)			
frequency	Fog Visibility 50 m (0.1 g/m^3)	Excessive Rain - ER (150 mm/hr)	Heavy Rain - HR (25 mm/hr)	Drizzle (0.25 mm/hr)		fog penalty	ER penalty	HR penalty	Drizzle penalty
28 GHz	0.19	28.18	5.17	0.17		-224.81	0.18	-1.83	-0.22
39 GHz	0.09	38.18	7.31	0.08		-224.91	10.18	0.31	-0.31
60 GHz	0.04	45.61	9.49	0.03		-224.96	17.61	2.49	-0.36
180 THz	225.00	28.00	7.00	0.39					

FIGURE 6B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/31565

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H04B 10/00, 10/04, 10/06, 10/10, 10/105, 10/22
US CL : 359/145, 159, 154, 164, 172; 455/151.2

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 359/145, 159, 154, 164, 172; 455/151.2

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 5,946,120 A (CHEN) 31 August 1999 (31.08.1999), abstract, Fig. 1, column 3	1-3, 25, 27, 29, 31, 34, 35, 38 ---------- 4-24, 26, 28, 30, 32, 33, 36, 37, 39-56
Y	US 6,285,481 B1 (PALMER) 04 September 2001 (04.09.2001), Fig. 1, column 6	4-24, 26, 28, 30, 32, 33, 36, 37, 39-56
Y	US 5,479,595 A (ISRAELSSON) 26 December 1995 (26.12.1995), Fig. 1, abstract, column 3-6	4-24, 26, 28, 30, 32, 33, 36, 37, 39-56
Y	US 6,049,593 A (ACAMPORA) 11 April 2000 (11.04.2000), abstract, Figure 3a	4-24, 26, 28, 30, 32, 33, 36, 37, 39-56
Y	US 5,034,997 A (IWASAKI) 23 July 1991 (23.01.1991), Fig. 3A, 3B	4-24, 26, 28, 30, 32, 33, 36, 37, 39-56

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 January 2002 (14.01.2002)	05 FEB 2002

Name and mailing address of the ISA/US	Authorized officer
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